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Hydrogen Refueling Analysis of Fuel Cell Heavy-Duty Vehicles Fleet

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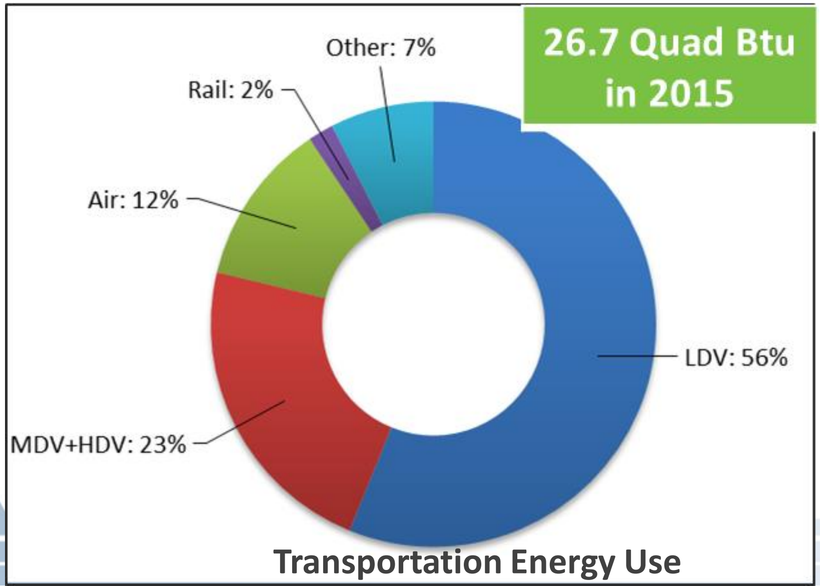
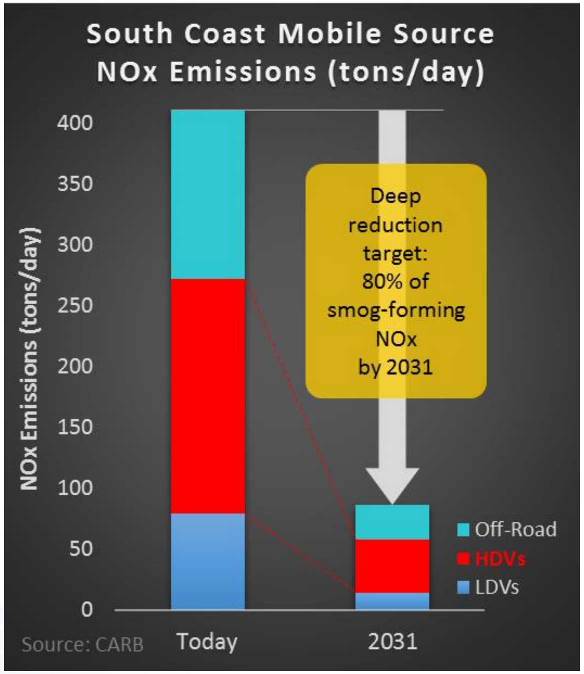
Relevance/Impact

Growing interest in zero-emissions medium- and heavy-duty vehicles (M/HDV) in transportation

- M/HDV is the second largest and fastest growing energy consumer in transportation, accounting for significant energy use and air emissions.
  - ➢ Energy share expected to grow to 30% of total transportation energy by 2040
- M/HDV NOx and PM10 emissions comparable to LDV emissions (0.94 and 0.8 of LDV emissions in 2014, respectively)
- CA targets 80% reduction of mobile source NOx emissions by 2030 → role for ZEV HDV → Fuel cells for transit buses

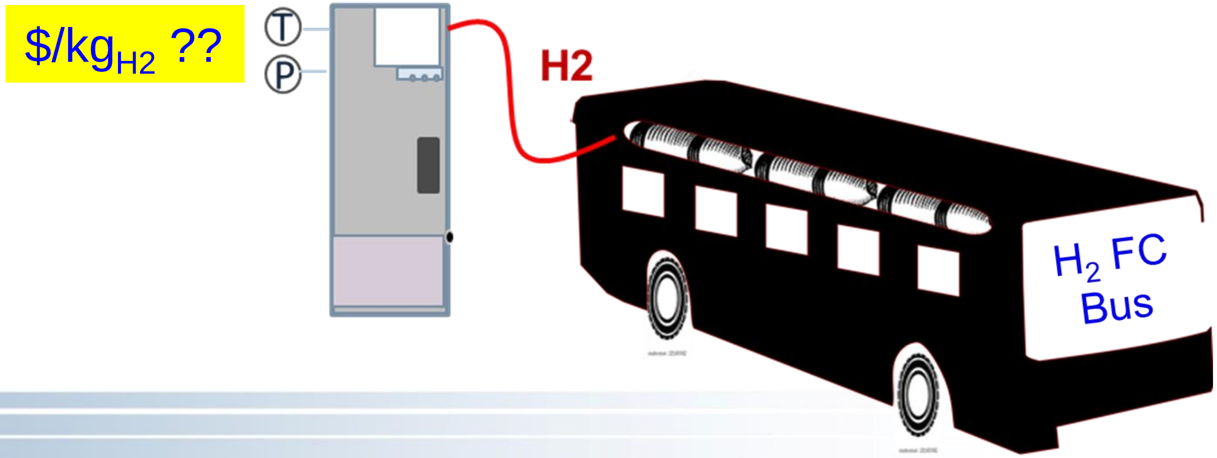




Relevance

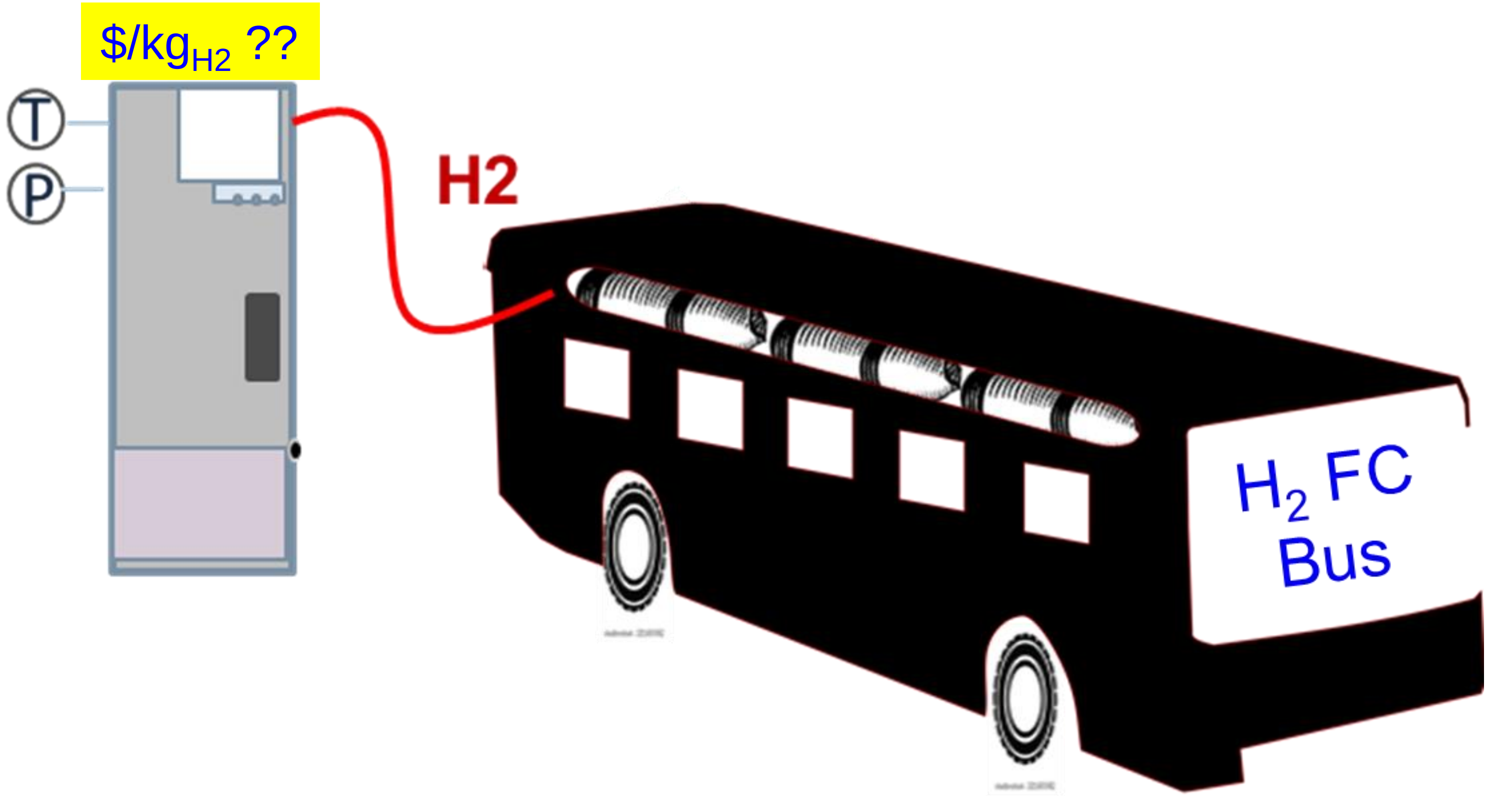
Fuel Cell Vehicles can address energy and emissions problems, but at what cost?

- Gap exists in the literature regarding HDV hydrogen fueling cost
  - ➢ Interest in station design and cost reduction potential with increased throughput
- Hydrogen fueling cost for HDV is different from LDV
  - ➢ With respect to fueling pressure, fill amount, fill rate, fill strategy, precooling requirement, etc.
- **DOE and industry stakeholders seek evaluation of key parameters impacting hydrogen fuel cell HDV fueling cost**
  - ➢ New modeling and analysis is needed to inform DOE of potential challenges to achieving cost competitiveness for fuel cell HDV applications



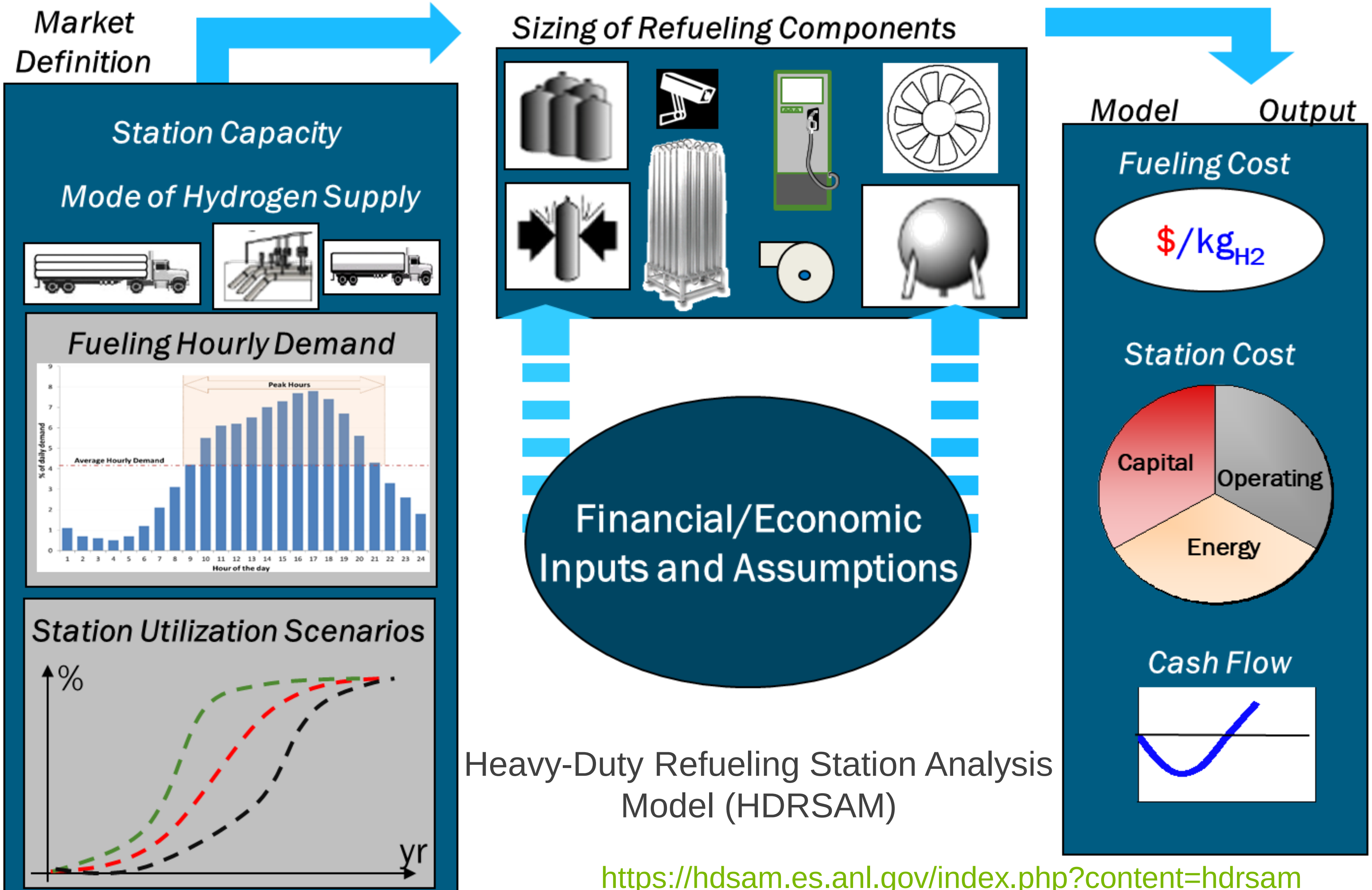
Objective

- Evaluate impacts of key market, technical, and economic parameters on refueling cost [$\$/kg_{H2}$] of heavy-duty fuel cell (FC) vehicles
  - ✓ Evaluate fuel cell bus fleet as a surrogate for other M/HDVs



Approach: *Develop a refueling model for FC HDV fleet*

- Systematically examines impact of various parameters



Heavy-Duty Refueling Station Analysis Model (HDRSAM)

https://hdsam.es.anl.gov/index.php?content=hdrsam

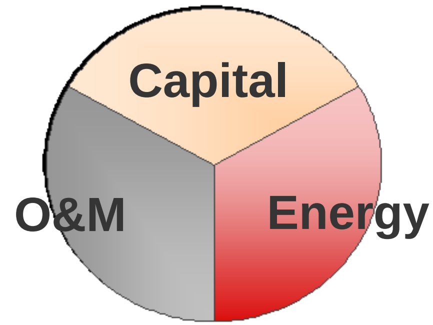
HDRSAM Model Outputs

HDRSAM characterizes the economics of a user-defined station

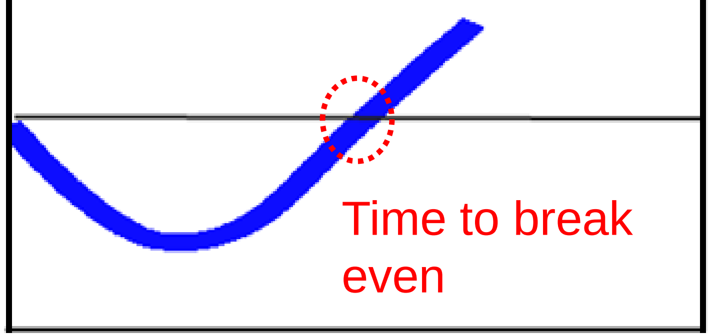
Station Levelized Cost

$\$/kg\_H_2$

Contributions to Levelized Cost



Cumulative Cash Flow



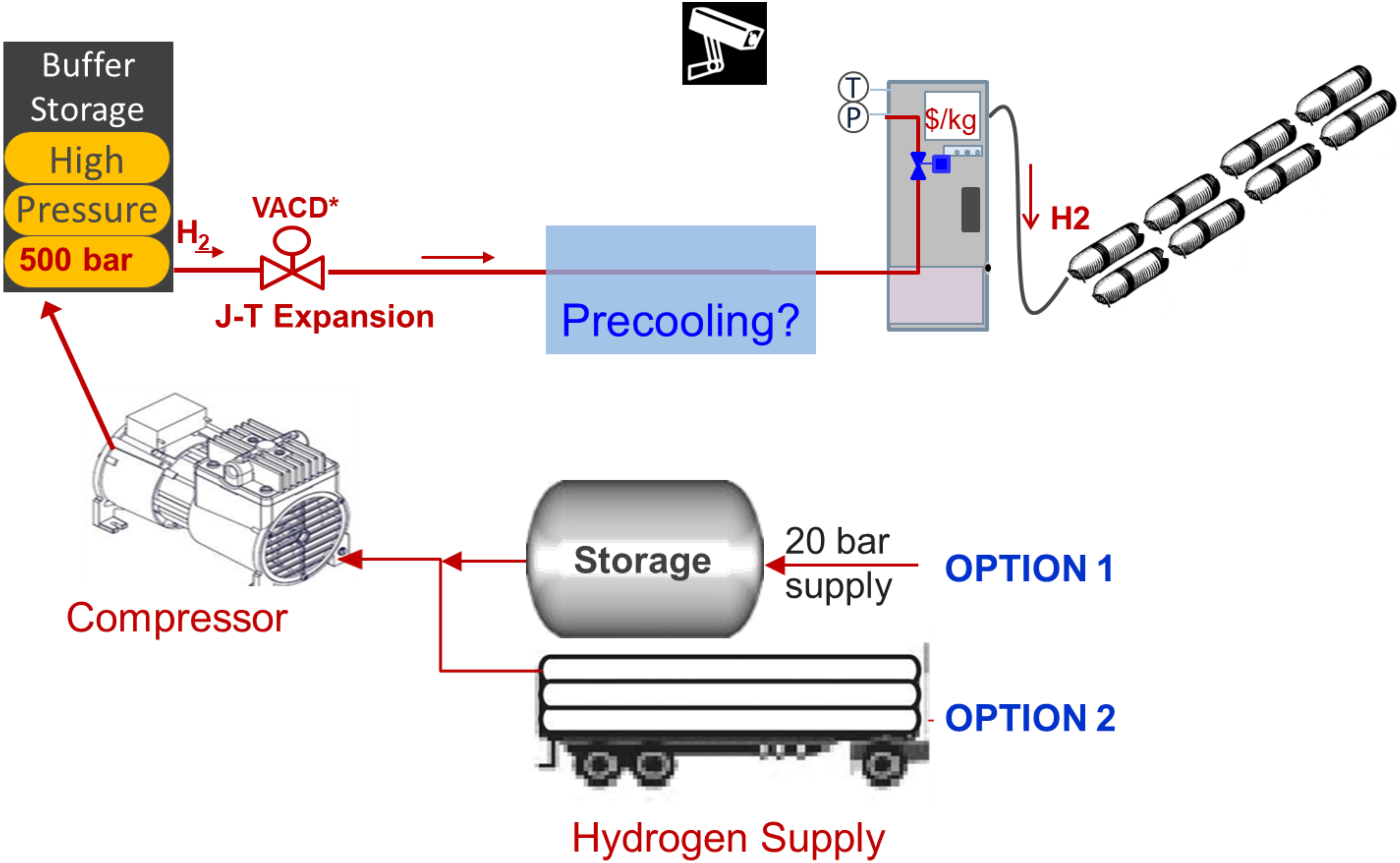
Contribution of Station Components to H_2 Cost

Parameters to evaluate

- Market parameters:
  - Fleet size (10, 30, 50, 100 buses)
  - Hydrogen supply (20 bar gaseous, liquid tanker, tube trailer)
  - Market penetration (production volume of refueling components, i.e., low, med, high)
- Technical parameters:
  - Refueling pressure (350 bar and 700 bar)
  - Tank type (III, IV)
  - Dispensed amount per vehicle (20 kg, 35 kg)
  - Fill rate (1.8, 3.6, 7.2 kg/min)
  - Fill strategy (back-to-back, staggered, number of dispensers)
  - Refueling configuration (e.g., compression vs. pumping)
  - SAE TIR specifies fueling process rates and limits (not a protocol)

- Parameters in red color are defaults for parametric analysis

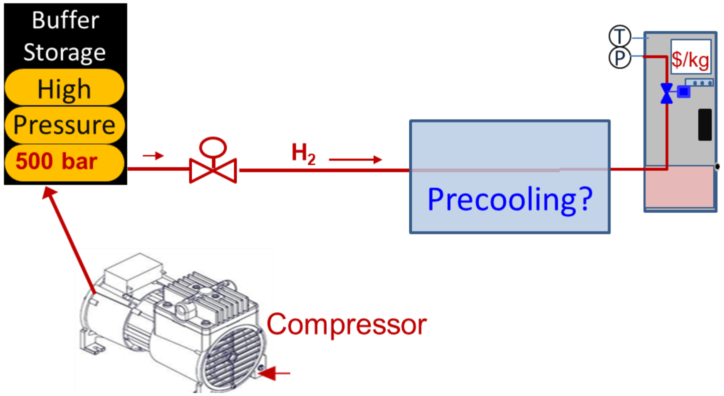
Refueling configuration options for gaseous H_2 supply

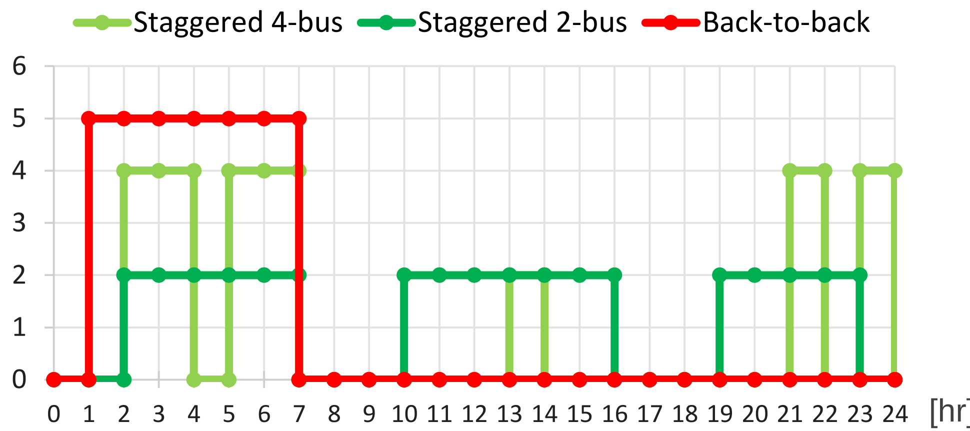


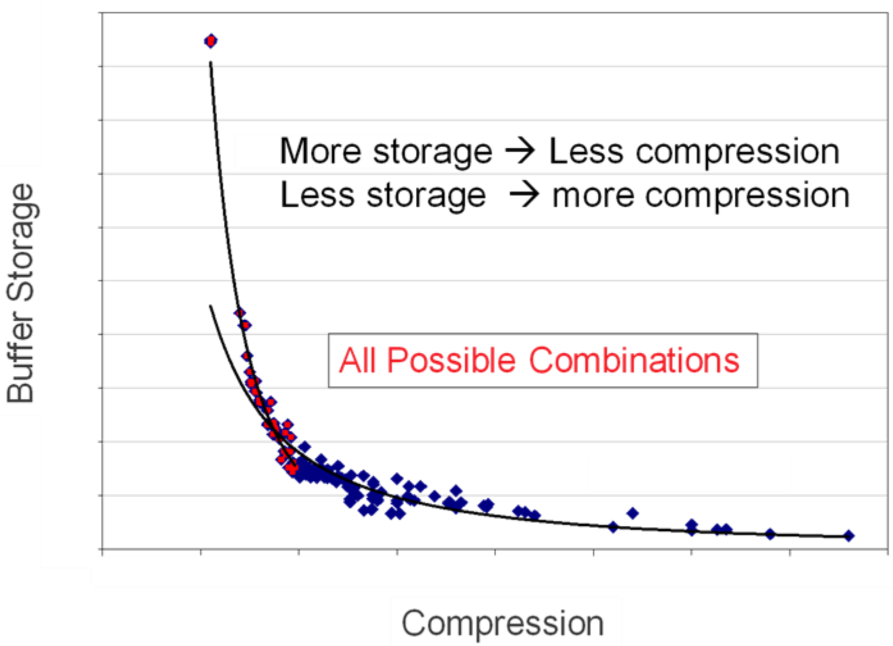
*variable area control device

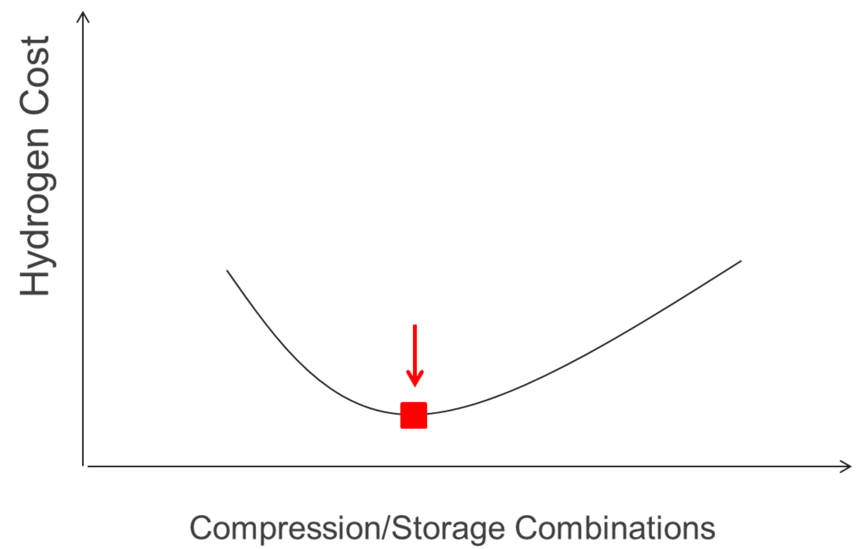
Optimization

HDRSAM searches for optimum (lowest levelized cost) station configuration



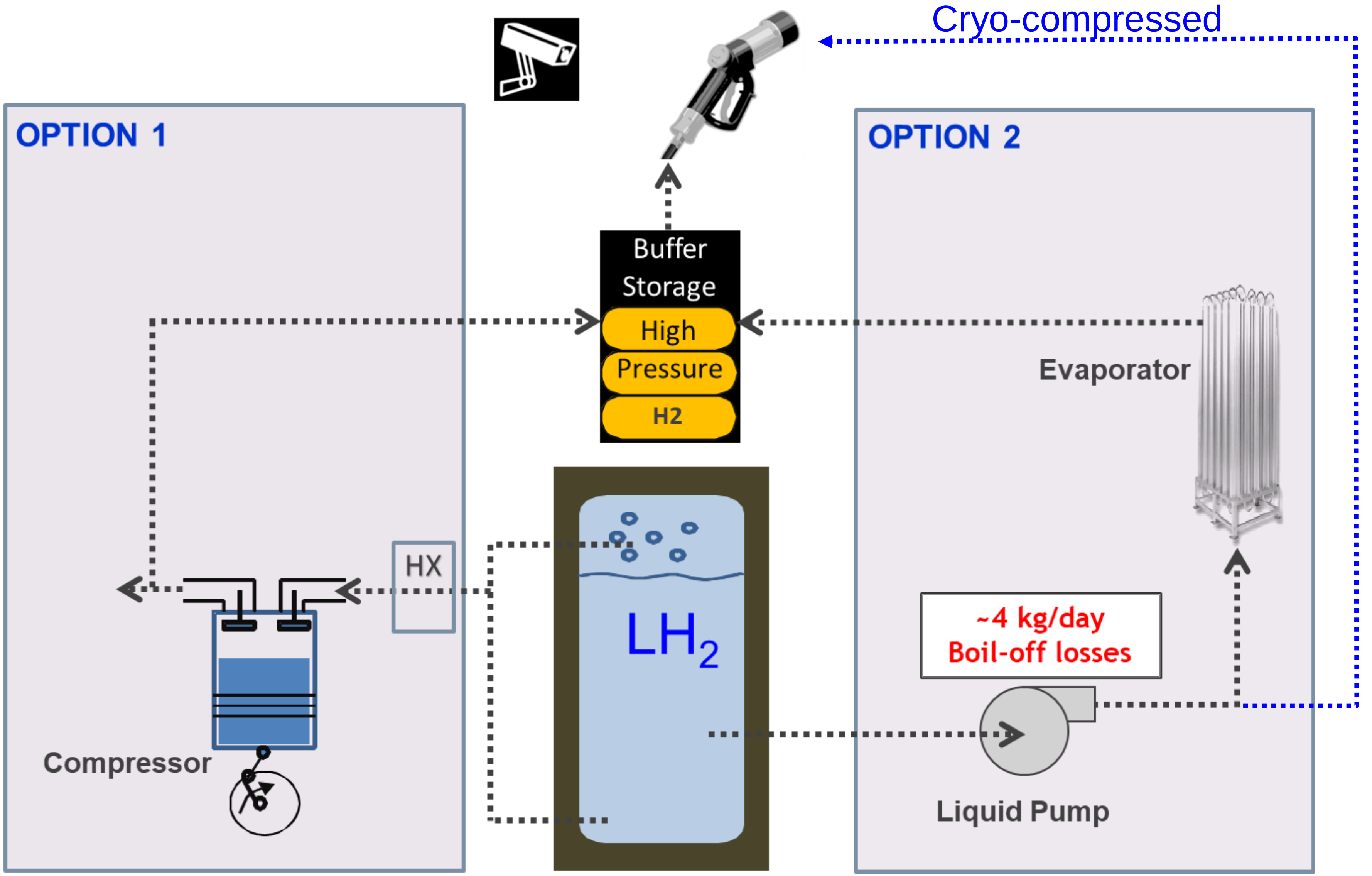




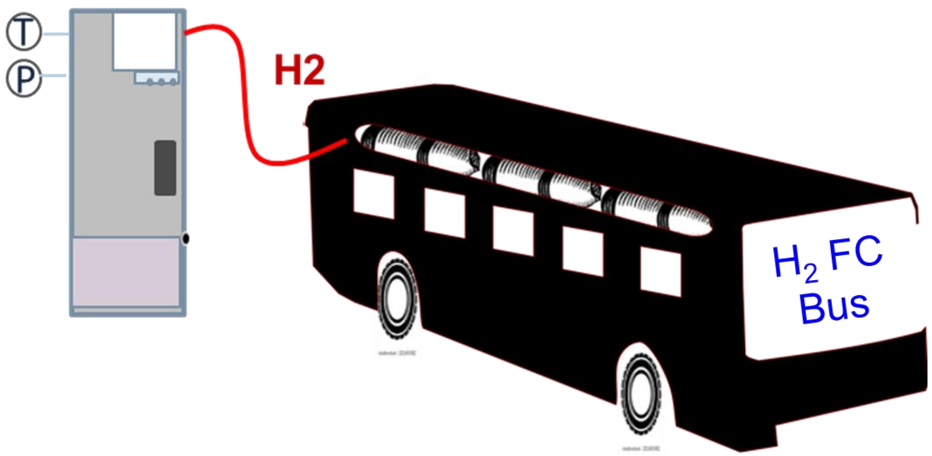


https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/nexant_h2a.pdf

Refueling configuration options with LH_2 delivery



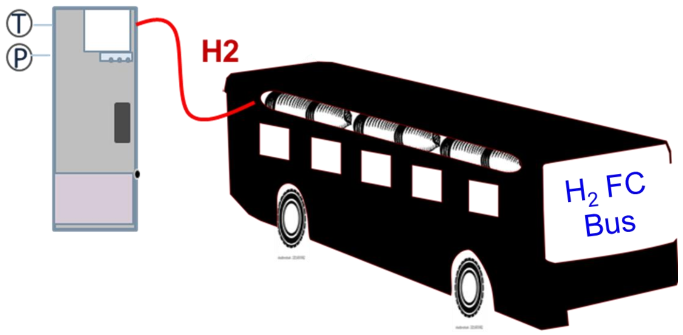
Evaluate precooling requirement for various vehicle tank types, fill pressures and refueling rates

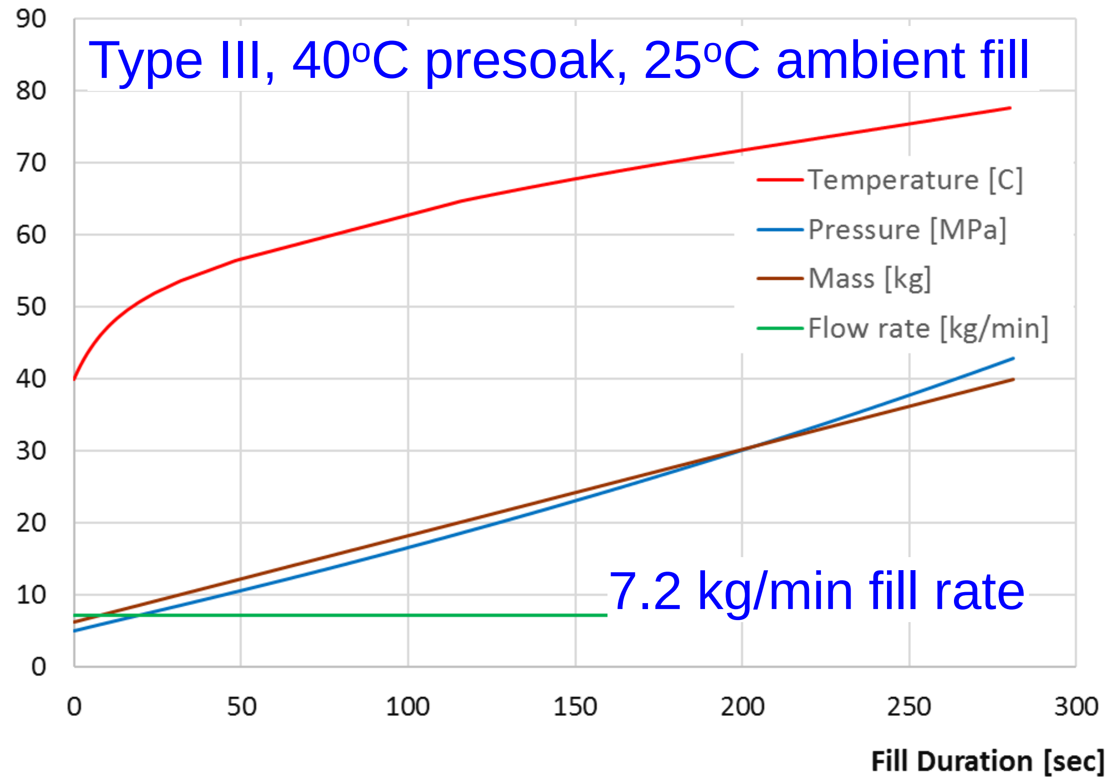


Bus Onboard Storage System (350 bar, Type III)	
Storage System Capacity [kg]	40
Number of Tanks	8
Tank Capacity [kg]	5
Initial tank pressure [MPa]	5
Geometry	
Outer Diameter [in]	17.74
Thickness [in]	1.78
Length [in]	88.7
Volume [L]	208

- Simulated tank fills with H2SCOPE Model
  - ✓ Type III and Type IV (350 bar and 700 bar)
- Simulated various refueling rates (1.8, 3.6, and 7.2 kg/min)
- Solved physical laws to track mass, temperature, and pressure
  - ✓ Determine precooling requirement

Type III tanks do not require precooling at all fill rates





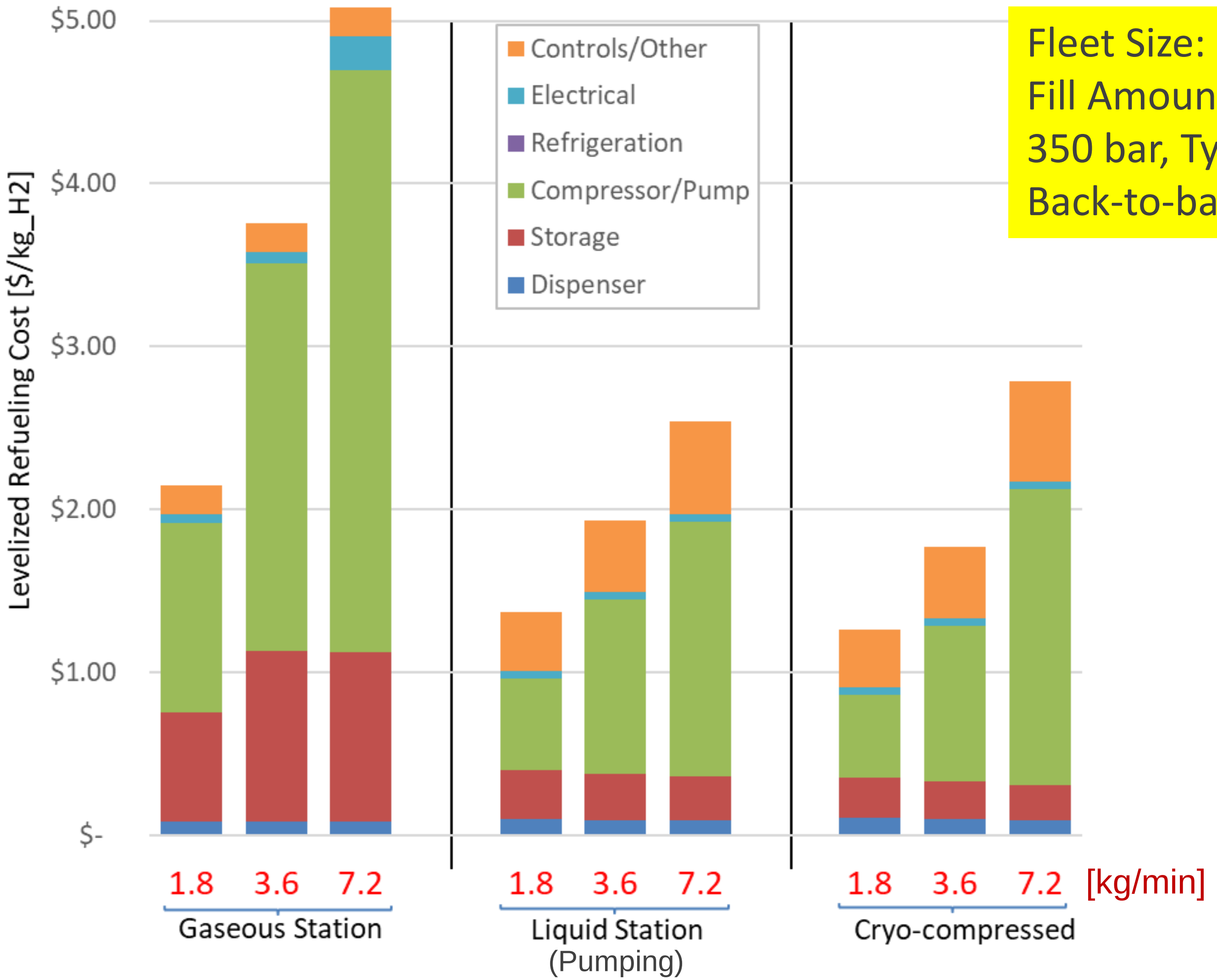
Tank Type	Fueling Rate [kg/min]	Required Precooling Temperature [°C]
III (350 bar)	1.8	No precooling required
	3.6	No precooling required
	7.2	No precooling required
IV (350 and 700 bar)	1.8	No precooling for 350 bar, 15°C for 700 bar
	3.6	20°C for 350 bar, 0°C for 700 bar
	7.2	5°C for 350 bar, -10°C for 700 bar

Cost estimates for sourcing H_2 to refueling station (near-term)

- Cost of liquid H_2 delivered to refueling station (3.5-4 MT), 100-500 miles transportation distance:
  - $6-8/kg_$H_2$
- Cost of onsite water-electrolysis H_2 production (@ $1000/kW) + compression:
  - $7-10/kg_$H_2$
- Cost of onsite SMR H_2 production + compression:
  - $3-4/kg_$H_2$ (additional storage cost may be warranted)

H_2 production/transportation cost is additional to refueling cost

Impact of *fueling rate* on refueling cost

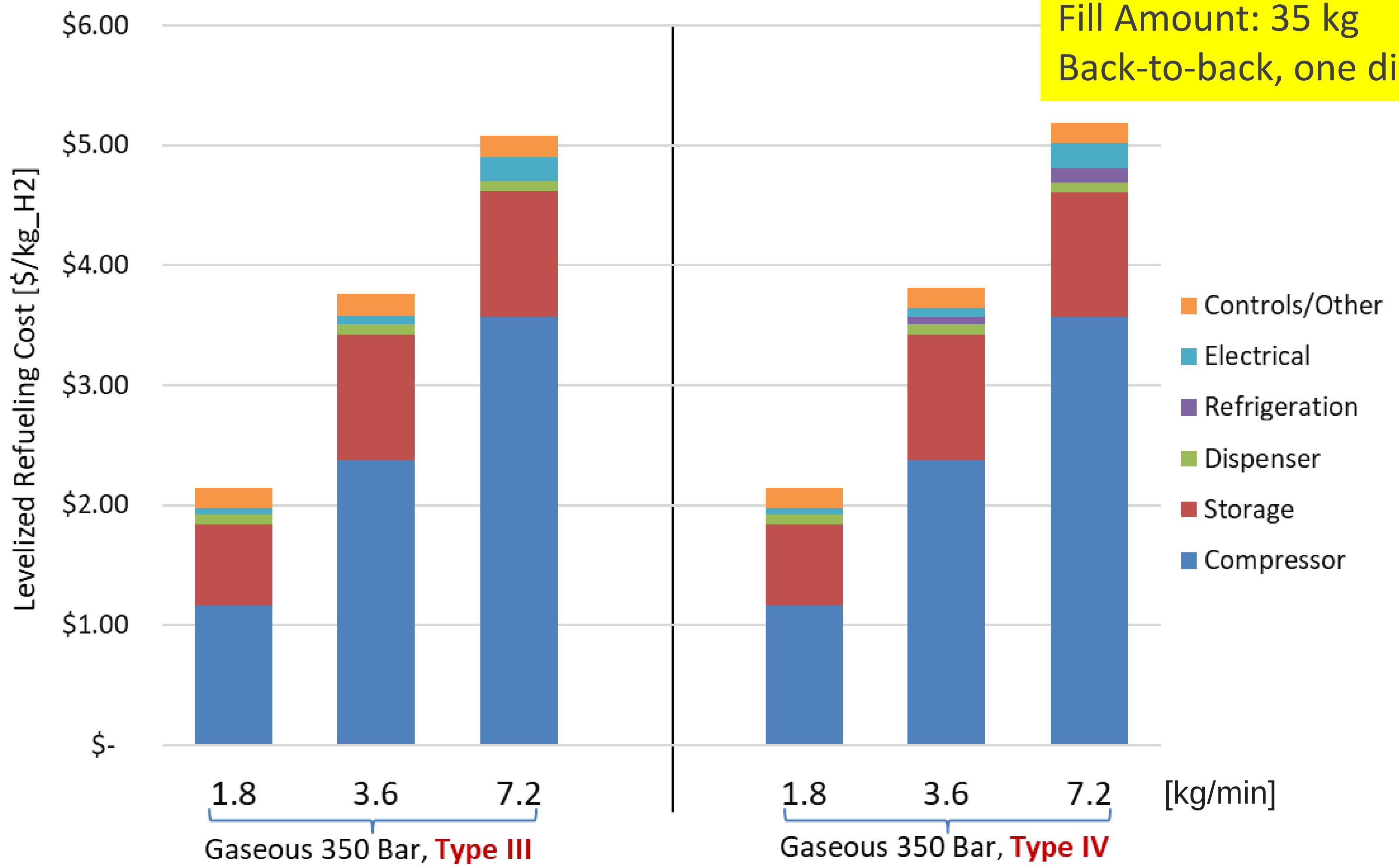


Fleet Size: 30 buses
Fill Amount: 35 kg
350 bar, Type III tanks
Back-to-back, one dispenser

- Faster fills require higher capacity equipment and result in higher cost
- Liquid stations can handle faster fills with less cost increase

Impact of *tank type* on refueling cost

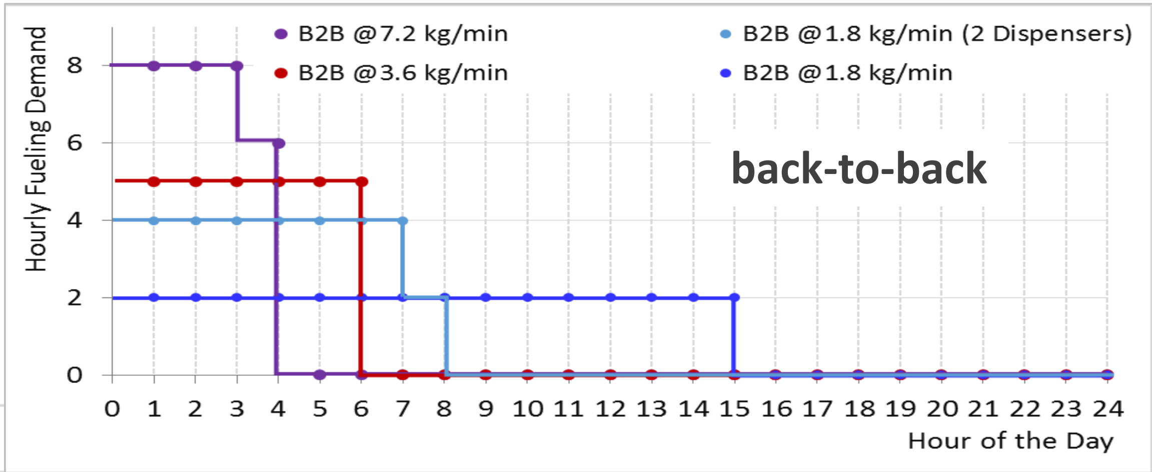
Fleet Size: 30 buses
Fill Amount: 35 kg
Back-to-back, one dispenser

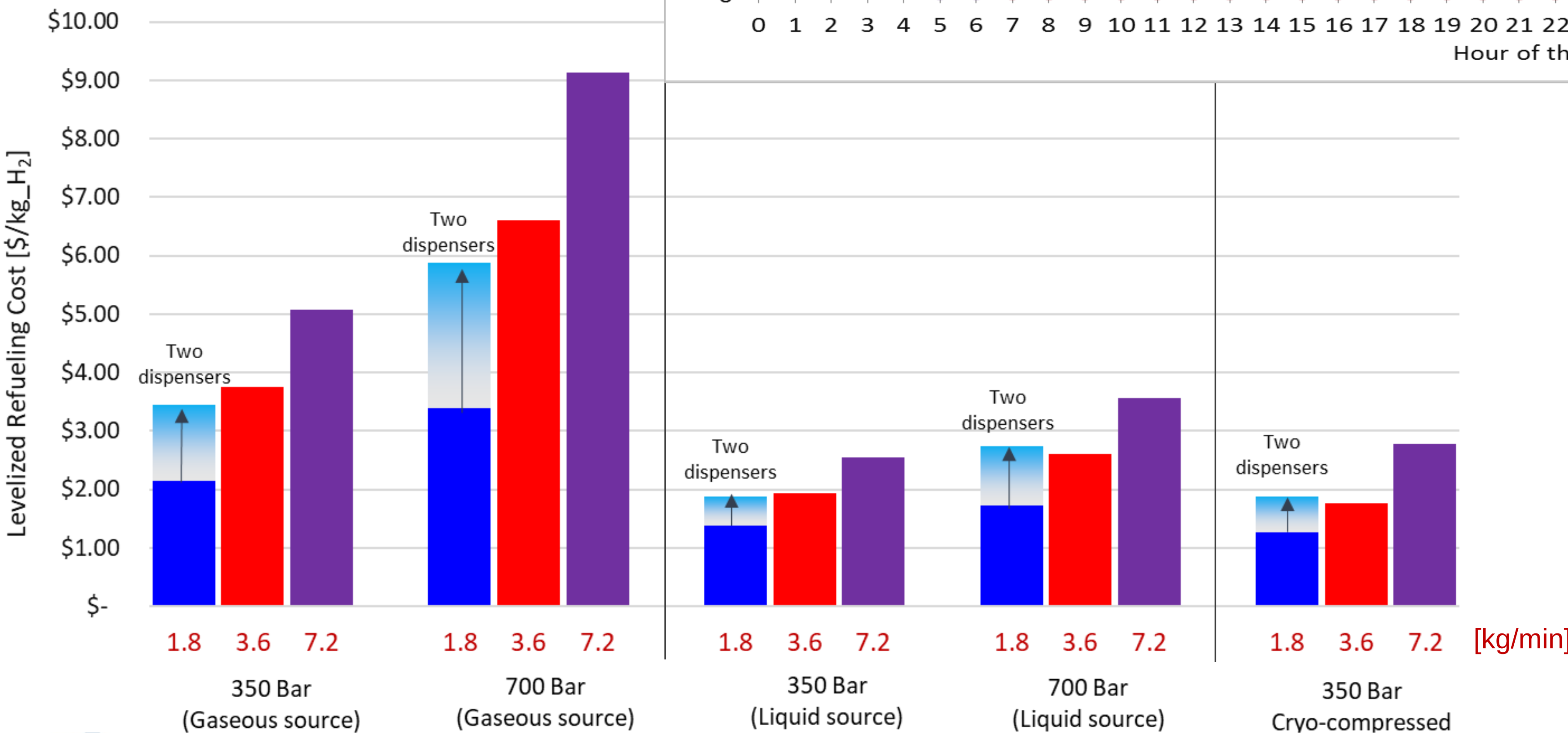


- Comparable refueling cost for type III and type IV tanks
- Refrigeration cost is relatively small
- Can avoid precooling in Type IV with fill rate slightly slower than 3.6 [kg/h]

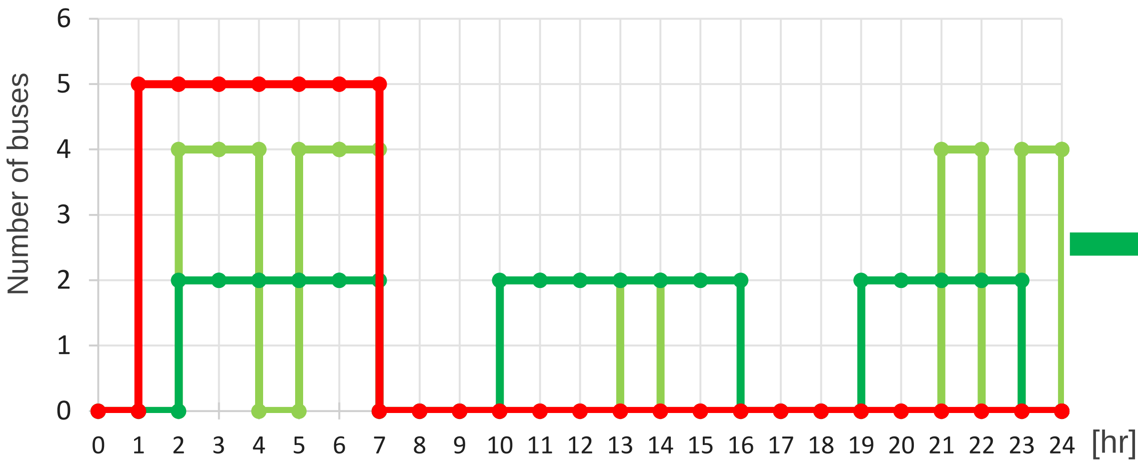
Impact of fueling pressure & tank type on fueling cost

Fleet Size: 30 buses
Fill Amount: 35 kg
Type IV Tank for gaseous dispensing



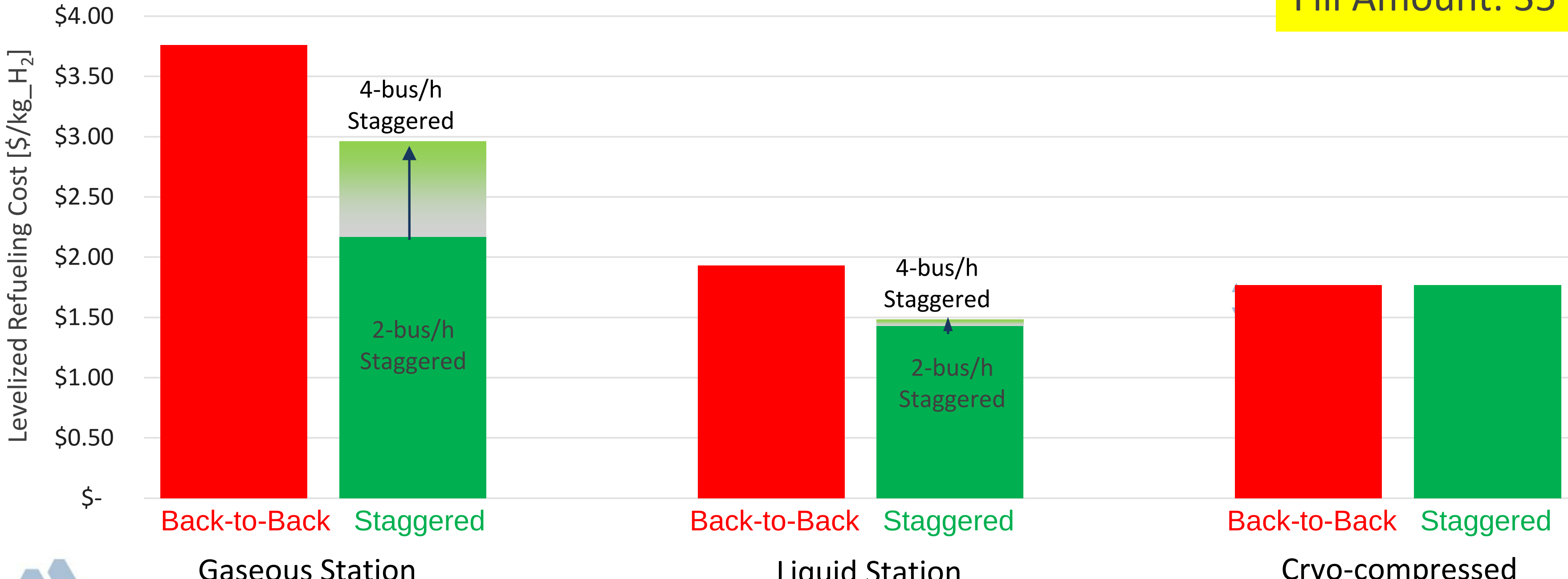


Staggered fueling can reduce fueling cost vs. back-to-back fills

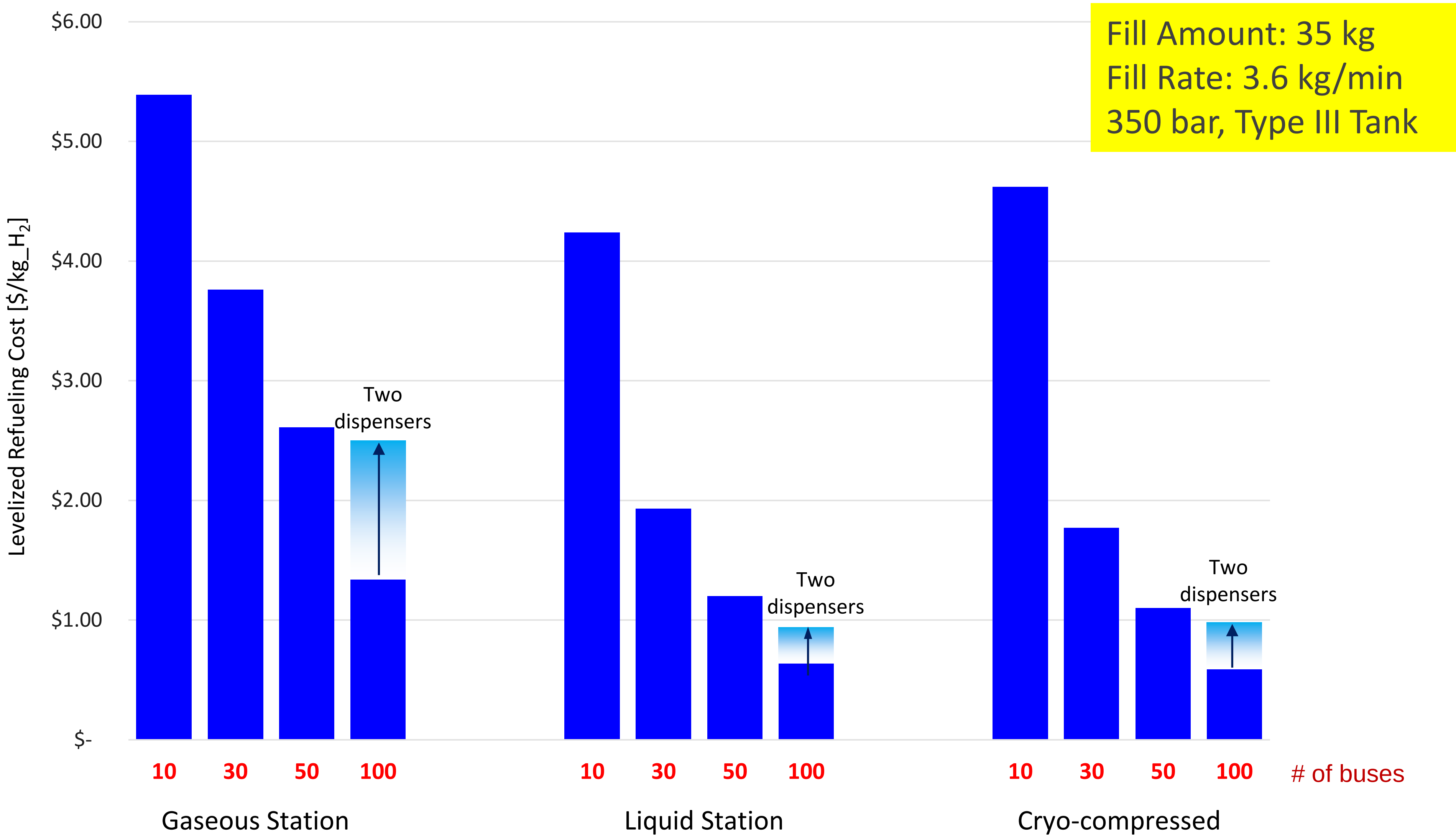


Staggered refueling may be restricted by bus availability for refueling

Fleet Size: 30 buses
Fill Amount: 35 kg



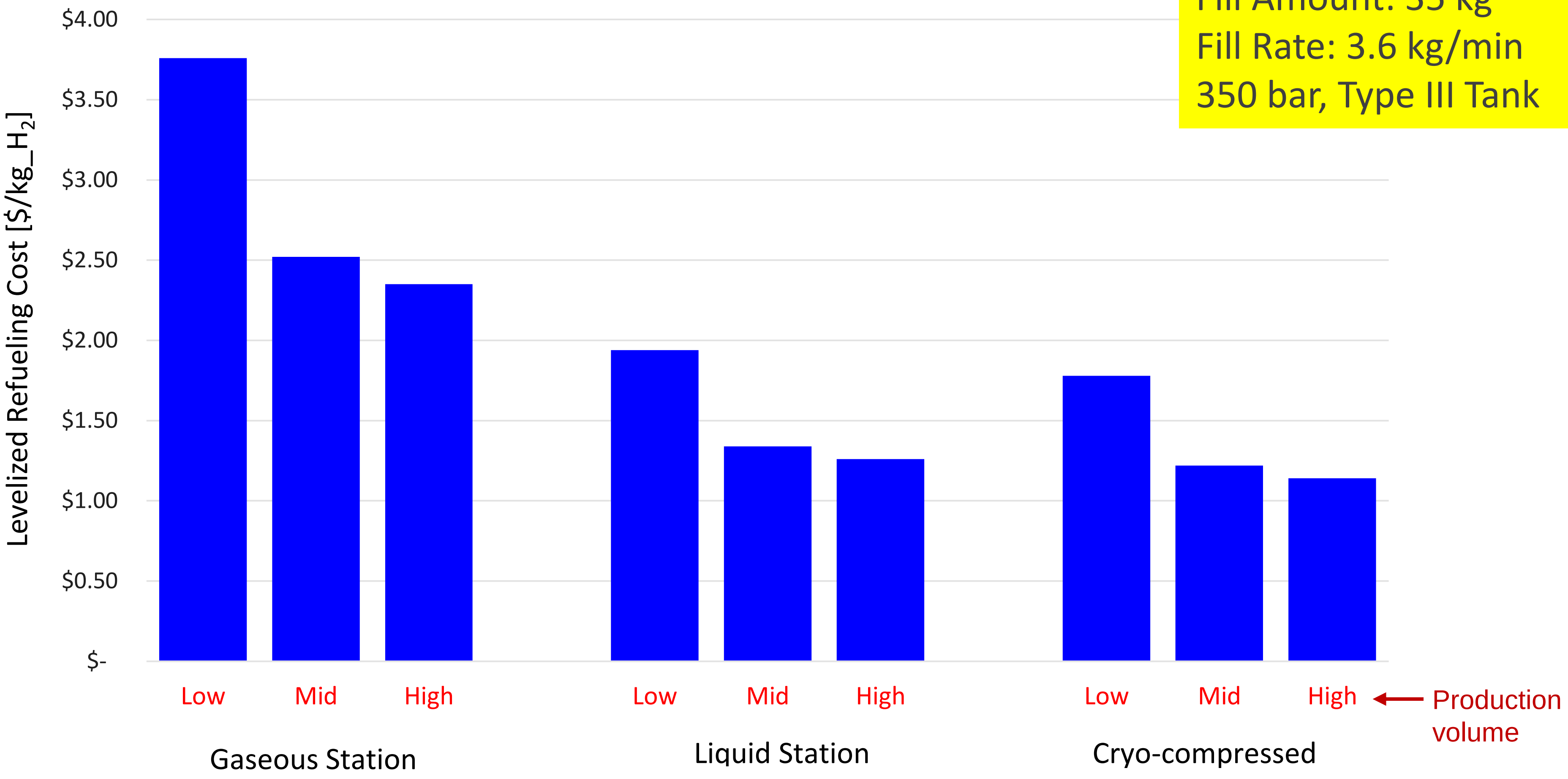
Impact of fleet size (demand) on refueling



- Strong economies of scale with fleet size (daily demand)
  - ✓ fueling cost can drop to ~$1/kg$_{H2}$ with large fleet size
- Liquid station, in general, provides a lower cost option

Impact of station equipment production volume on refueling cost

Fleet Size: 30 Vehicles
Fill Amount: 35 kg
Fill Rate: 3.6 kg/min
350 bar, Type III Tank



- Refueling cost can be reduced to $1.5/kg_{H2}$ with high production volume of fueling components (with learning) for a modest fleet size (30 buses)

Summary

- Lower refueling cost of HDV fleet compared to refueling LDVs
- Liquid station, in general, provides a lower cost option for HDV fleet refueling compared to gaseous stations (cost of H_2 source is additional and vary by source)
- Strong economies of scale can be realized with fleet size and fill amount (impacting station demand/capacity)
  - ✓ ~$1/kg_$H_2$ for 100 FC bus fleet with today equipment cost
- Faster fills require higher capacity equipment and result in higher fueling cost
- Back-to-back fills increase fueling cost with higher fill rates, while staggered fueling reduces fueling cost, even at higher fill rates
- Refueling cost can be reduced to $1-$1.5/kg_{H2} for large fleets and high production volume of fueling components
- Type IV tanks do not appreciably increase fueling cost compared to type III tanks
- 700 bar refueling appreciably increases fueling cost compared to 350 bar, especially for gaseous H_2 sources
- Future cryo-compressed tanks offer similar or lower refueling cost compared to gaseous refueling

Acknowledgments

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Thank You!!!

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